The Missing Difference Problem, and its Applications to Counter Mode Encryption

Gaëtan Leurent, Ferdinand Sibleyras

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Introduction

- **Cryptography:** Alice encrypts then sends messages to Bob.
- **Symmetric:** Alice and Bob share the same key.
- **Public channel:** Eve (attacker) can see and/or manipulate what is being sent.

Introduction

Block Cipher

$$E_k : \{0,1\}^n \to \{0,1\}^n$$

A family of **permutations** indexed by a key (AES, 3DES, ...) where n is the bit size of the permutation or block's size.

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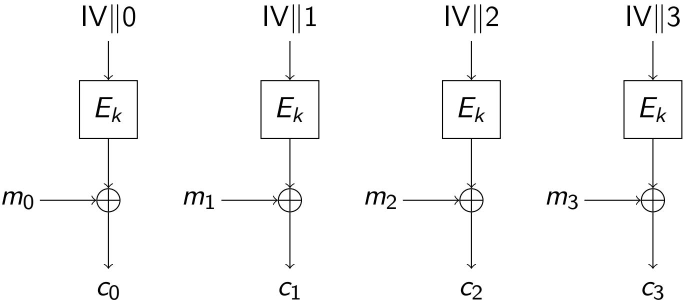
Mode of operation

Describes how to use a **block cipher** along with a plaintext message of **arbitrary length** to achieve some concrete cryptographic goals.

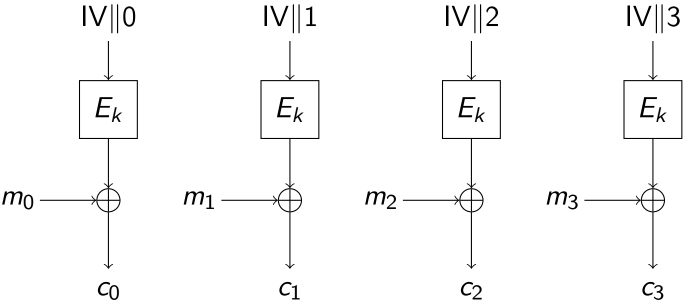
The counter mode (CTR)



m_i : The plaintext.
c_i : The ciphertext.
E_k : The block cipher.
IV : The Initialisation Value.

$$c_i = E_k(IV\|i) \oplus m_i$$

The counter mode (CTR)



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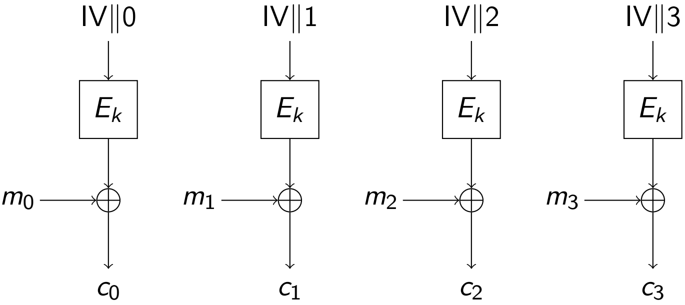

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$$c_i = E_k(\mathrm{IV}\|i) \oplus m_i$$

Akin to a stream cipher: keystream XORed with the plaintext.
Inputs $\mathrm{IV}\|i$ to the block cipher never repeat.

The counter mode (CTR)

Let $K_i = E_k(\mathrm{IV} \| i)$ the ith block of keystream.

- If E_k is a good Pseudo-Random Function (PRF) then all K_i are random and this is a one-time-pad.
- A block cipher is a Pseudo-Random Permutation (PRP) therefore K_i are all distinct: $K_i \neq K_j \; \forall i \neq j$.

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Security proof (σ the number of blocks)

$$\mathbf{Adv}^{\mathrm{IND}}_{\mathrm{CTR}\text{-}E_k}(\sigma) \leq \mathbf{Adv}^{\mathrm{PRF}}_{E_k}(\sigma) \leq \mathbf{Adv}^{\mathrm{PRP}}_{E_k}(\sigma) + \sigma^2/2^{n+1}$$

Distinguisher

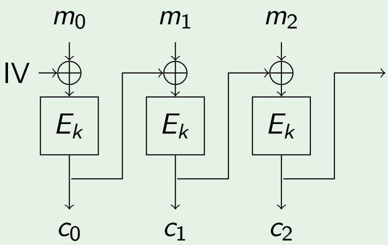
After $\sigma \simeq 2^{n/2}$ encrypted blocks we expect a collision on the K_i with high probability in the case of a random ciphertext.
That is the birthday bound coming from the birthday paradox.

CBC and CTR

Both modes are:

- widely deployed
- proven secure up to birthday bound ($2^{n/2}$)
- matching distinguishers at the proof's bound

CBC mode



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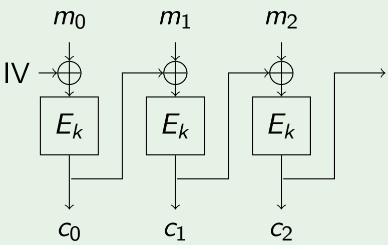

Folklore assumptions [Ferguson, Schneier, Kohno]

CTR leaks very little data. [...] It would be reasonable to limit the cipher mode to 2^{60} blocks, which allows you to encrypt 2^{64} bytes but restricts the leakage to a small fraction of a bit.
When using CBC mode you should be a bit more restrictive. [...] We suggest limiting CBC encryption to 2^{32} blocks or so.

The counter mode (CTR)

From a distinguishing attack to a plaintext recovery attack ?

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- We can observe repeated encryptions of a secret S that is $c_j = K_j \oplus S$ for many different j.

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Main Idea

Collect many keystream blocks K_i and encryptions of secret block $c_j = K_j \oplus S$; then look for a value S such that $K_i \oplus c_j \neq S \; \forall i \neq j$.

Missing difference problem

The missing difference problem

- Given $\mathcal{A}$ and $\mathcal{B}$, and a hint $\mathcal{S}$ three sets of n-bit words
- Find $S \in \mathcal{S}$ such that:

$$\forall (a, b) \in \mathcal{A} \times \mathcal{B},\ S \neq a \oplus b\ .$$

Missing difference problem

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Collect many keystream blocks $K_i \in \mathcal{A}$ and encryptions of secret block $c_j = K_j \oplus S \in \mathcal{B}$; then look for a value $S \in \mathcal{S}$ such that $\forall (a,b) \in \mathcal{A} \times \mathcal{B},\ S \neq a \oplus b$.

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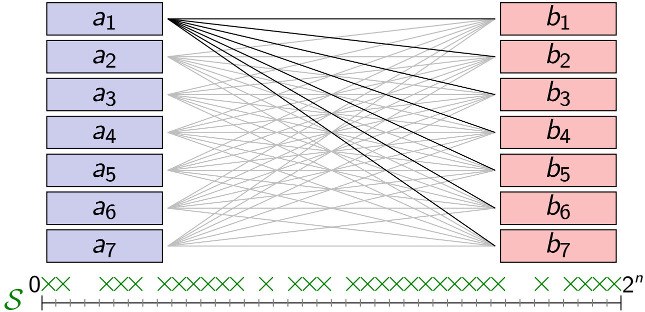
Simple Sieving Algorithm [McGrew, FSE'13]



Compute all $a_i \oplus b_j$, remove results from a sieve $\mathcal{S}$.

Analysis: case $|\mathcal{S}| = 2^n$ via coupon collector problem

- To exclude 2^n candidates of S, we need $n \cdot 2^n$ values $a_i \oplus b_j$
  - Lists $\mathcal{A}$ and $\mathcal{B}$ of size $\sqrt{n} \cdot 2^{n/2}$. Complexity: $\tilde{\mathcal{O}}(2^n)$

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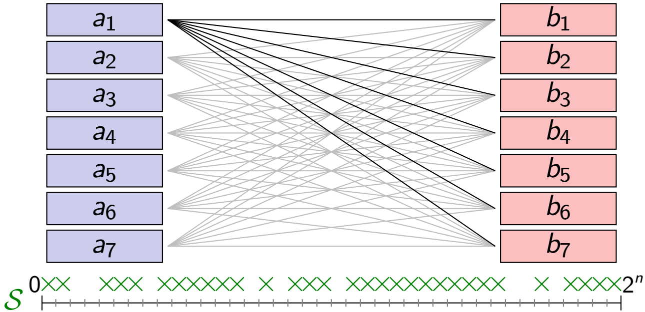
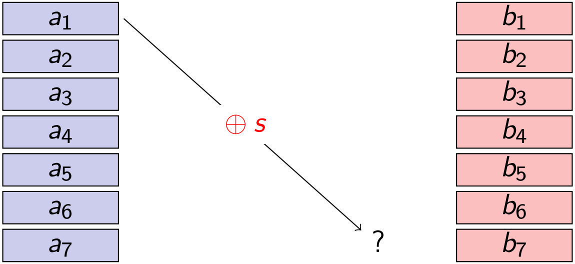


Compute all $a_i \oplus b_j$, remove results from a sieve $\mathcal{S}$.

Analysis: case $|\mathcal{S}| = 2$

- To exclude 1 candidate of S, we need 2^n values $a_i \oplus b_j$
  - Lists $\mathcal{A}$ and $\mathcal{B}$ of size $2^{n/2}$. Complexity: $\tilde{\mathcal{O}}(2^n)$

Searching Algorithm [McGrew, FSE'13]



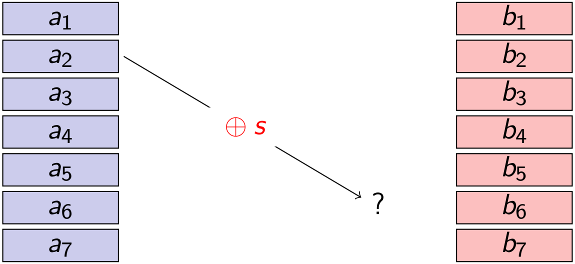
- Make a guess and verify.

Try Guess (s)

for a **in** $\mathcal{A}$ **do**
  if $(s \oplus a) \in \mathcal{B}$ **then**
    return 0
return 1

Searching Algorithm

[McGrew, FSE'13]



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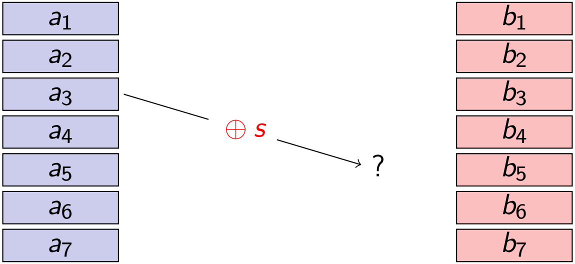

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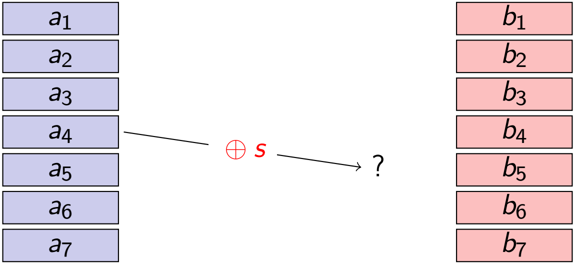

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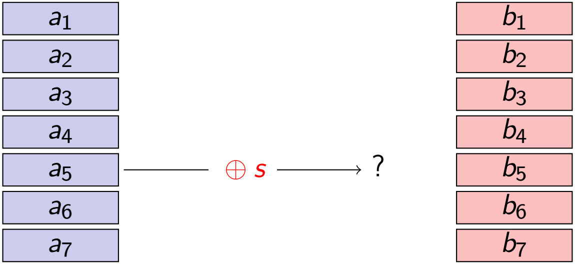

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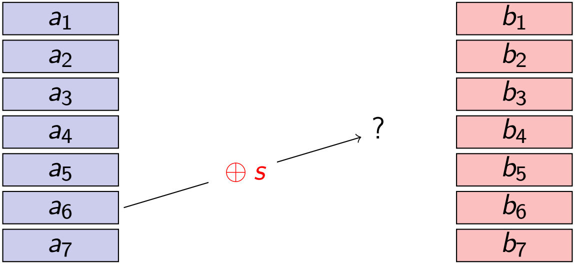

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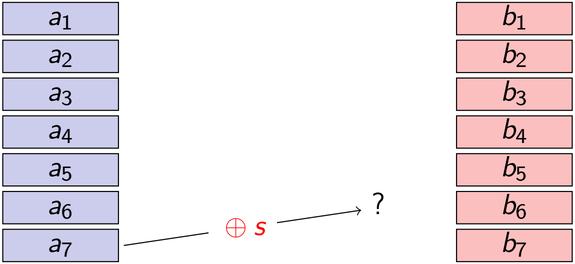

- Make a guess and verify.
- Complexity $\tilde{\mathcal{O}}(2^{n/2}\sqrt{|\mathcal{S}|})$ with unbalanced $\mathcal{A}$, $\mathcal{B}$.

Try Guess (s)

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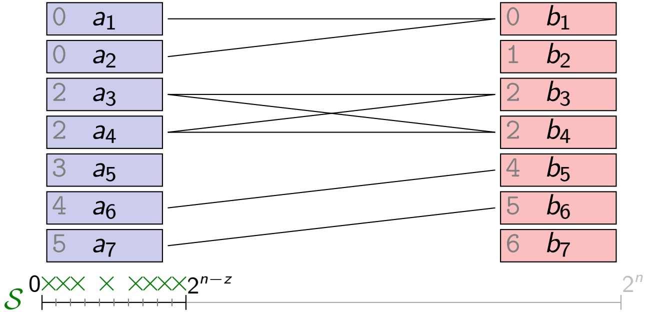
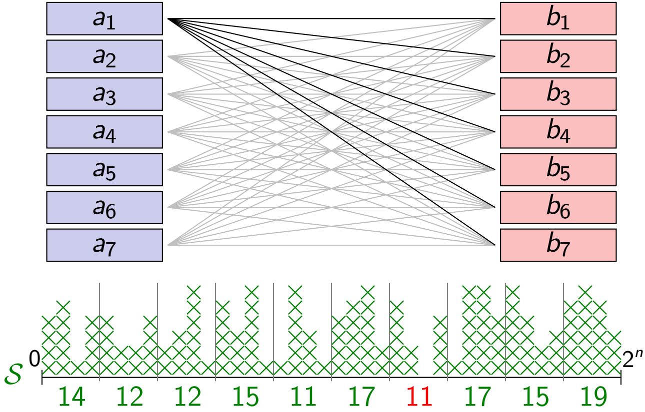
Known-prefix Sieving



- Assume S starts with z zero bits (more generally, linear subspace with $\dim\langle\mathcal{S}\rangle = n - z$)
- Sort lists, consider a_i's and b_j's with matching z-bit prefix
- Complexity: $\tilde{\mathcal{O}}(2^{n/2} + 2^{\dim\langle\mathcal{S}\rangle})$
  - Looking for collision + needed number of collisions
- Complexity: $\tilde{\mathcal{O}}(2^{n/2})$ when $\dim\langle\mathcal{S}\rangle \leq n/2$

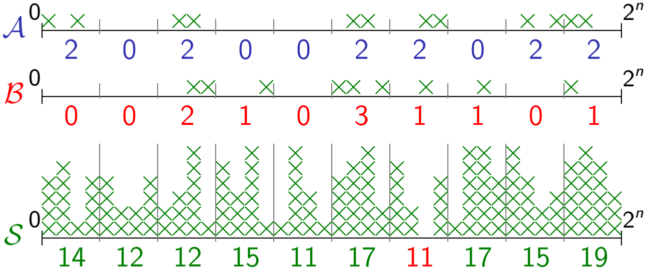
Fast Convolution Sieving



- Instead of computing full sieve, use buckets (*ie.* truncate)
- With enough data, missing difference has smallest bucket with high probability

Computing the sieve

- Count buckets for $\mathcal{A}$ and $\mathcal{B}$
  - $C_{\mathcal{X}}[i] = \left|\{x \in \mathcal{X} \mid T(x) = i\}\right|$



Computing the sieve

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  - $$\begin{aligned} C_{\mathcal{S}}[i] &= |\{(a,b) \in \mathcal{A} \times \mathcal{B} \mid T(a \oplus b) = i\}| \\ &= \sum_{a \in \mathcal{A}} |\{b \in \mathcal{B} \mid T(a \oplus b) = i\}| \\ &= \sum_{a \in \mathcal{A}} C_{\mathcal{B}}[i \oplus T(a)] \\ &= \sum_{j \in \{0,1\}^{n-t}} C_{\mathcal{A}}[j] \cdot C_{\mathcal{B}}[i \oplus j] \end{aligned}$$

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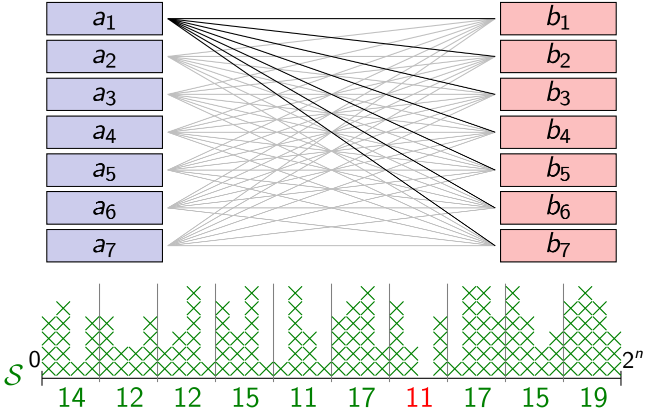
- Discrete convolution can be computed efficiently with the Fast Walsh-Hadamard transform!
  - Complexity: $\tilde{\mathcal{O}}(|C_{\mathcal{S}}|)$ for arbitrary $\mathcal{S}$

Fast Convolution Sieving



$$T(S) \stackrel{?}{=} \operatorname{argmin} C_{\mathcal{S}}[i]$$

And we can finish with Known-prefix Sieving to recover the rest.

- $2^{2n/3}$ queries, sieving with $2^{2n/3}$ buckets of $2^{n/3}$ elements

Missing difference problem algorithms

Algorithms for the missing difference problem

Simple Sieving	Complexity $\tilde{\mathcal{O}}(2^n)$	[McGrew]
Searching	Complexity $\tilde{\mathcal{O}}(2^{n/2}\sqrt{\lvert\mathcal{S}\rvert})$	[McGrew]
Known-prefix Sieving	Complexity $\tilde{\mathcal{O}}(2^{n/2} + 2^{\dim\langle\mathcal{S}\rangle})$	
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Fast Convolution Sieving Complexity $\tilde{\mathcal{O}}(2^{2n/3})$		

- Improved algorithm if $\mathcal{S}$ is a linear subspace
  - In particular still near optimal when $\dim\langle\mathcal{S}\rangle = n/2$
- Improved algorithm for arbitrary $\mathcal{S}$ at the cost of data
  - First algorithm with complexity below 2^n in that case

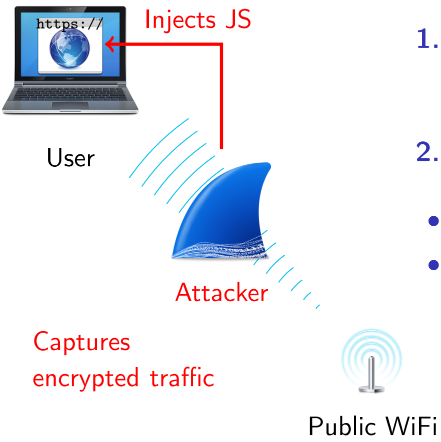
Back to Cryptanalysis

New Tools, New Attacks

Known-prefix $\rightarrow$ plaintext recovery on CTR mode

Fast Convolution $\rightarrow$ forgery on GMAC and Poly1305

BEAST Attack Setting [Duong & Rizzo 2011]



- Attacker has access to the network (*eg.* public WiFi)

1. Attacker uses JS to generate traffic
   - Tricks victim to malicious site
   - JS makes *cross-origin* requests
2. Attacker captures encrypted data

- Chosen plaintext attack
- Chosen-Prefix Secret-Suffix model $M \to \mathcal{E}(M \| S)$ [Hoang &al., Crypto'15]

Application to CTR (CPSS queries)

- Plaintext recovery using the known-prefix sieving algorithm
- Two kind of queries; half-block and full-block headers:

Q_1	H_1	S_1	S_2	S_3	S_4	
Q_2	H_1	H_2	S_1	S_2	S_3	S_4

1. Recover S_1 using the first block of each query:

$$\left.\begin{aligned}\mathcal{A} &= \{\mathcal{E}(H_1 \| H_2)\} \\ \mathcal{B} &= \{\mathcal{E}(H_1 \| S_1)\}\end{aligned}\right\} \to \text{Missing difference:} \quad 0 \| (S_1 \oplus H_2).$$

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$$\left.\begin{aligned}\mathcal{A} &= \{\mathcal{E}(H_1\|H_2)\}\\ \mathcal{B} &= \{\mathcal{E}(S_2\|S_3)\}\end{aligned}\right\}\rightarrow \text{Missing difference:}\ (S_2 \oplus H_1)\|(S_3 \oplus H_2).$$
4. ...

Application to CTR (CPSS queries)

Full Asymptotic Complexity

Queries	$\mathcal{O}(\sqrt{n} \cdot 2^{n/2})$
Memory	$\mathcal{O}(\sqrt{n} \cdot 2^{n/2})$
Time	$\mathcal{O}(n \cdot 2^{n/2})$

Impacts

How practical can be the plaintext recovery attack on CTR ?

- Mostly used with AES, famous 128-bit block cipher, as part of GCM. 90% of Firefox HTTPS traffic uses AES-GCM.
  - Requires 128×2^{64} bits $=$ 256 exbibytes over one session
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  - Requires 64×2^{32} bits = 32 GiB
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Sweet32 attack by Bhargavan and Leurent

Attack in the **BEAST setting with birthday bound complexity** already shown to be a threat over the web in recent work.
This is the **Sweet32** attack on CBC mode, more commonly used with 64-bit block ciphers.

Wegman-Carter Authentication Modes

- Wegman-Carter: build a MAC from a universal hash function and a PRF

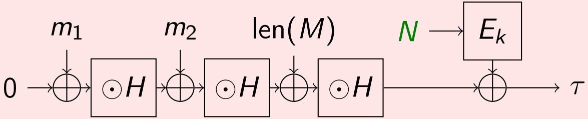
$$\mathrm{WC}(N, M) = H_{k_1}(M) \oplus F_{k_2}(N).$$

$$\mathbf{Adv}^{\mathrm{MAC}}_{\mathrm{WC}[H,F]} \leq \mathbf{Adv}^{\mathrm{PRF}}_{F} + \varepsilon + 2^{-n}$$

- Wegman-Carter-Shoup: use a block cipher as a PRF

$$\mathrm{WCS}(N, M) = H_{k_1}(M) \oplus E_{k_2}(N),$$

Example: Polynomial-based hashing (GMAC, Poly1305-AES)



Key recovery as a missing difference problem

- Fix two messages $M \neq M'$, capture MACs
  - $a_{\mathsf{i}} = \mathrm{MAC}(\mathsf{i}, M\ ) = H_{K_1}(M\ ) \oplus K_i$
  - $b_j = \mathrm{MAC}(j, M') = H_{K_1}(M') \oplus K_j$
  - $a_i \oplus b_j \neq H_{K_1}(M) \oplus H_{K_1}(M')$
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- For polynomial hashing, easy to recover universal hash key from $H_{K_1}(M) \oplus H_{K_1}(M')$
- Sieving algorithm recovers $H(M) \oplus H(M')$ with $\tilde{\mathcal{O}}(2^{n/2})$ queries and $\tilde{\mathcal{O}}(2^n)$ computations
  - Independently done in another Eurocrypt paper!

Optimal Forgeries Against Polynomial-Based MACs and GCM
Atul Luykx, Bart Preneel [Eurocrypt '18]

Key recovery as a missing difference problem

- Fix two messages $M \neq M'$, capture MACs
  - $a_i = \mathrm{MAC}(i, M) = H_{K_1}(M) \oplus K_i$
  - $b_j = \mathrm{MAC}(j, M') = H_{K_1}(M') \oplus K_j$
  - $a_i \oplus b_j \neq H_{K_1}(M) \oplus H_{K_1}(M')$
- For polynomial hashing, easy to recover universal hash key from $H_{K_1}(M) \oplus H_{K_1}(M')$

- Sieving algorithm recovers $H(M) \oplus H(M')$ with $\tilde{\mathcal{O}}(2^{n/2})$ queries and $\tilde{\mathcal{O}}(2^n)$ computations
  - Independently done in another Eurocrypt paper!

    Optimal Forgeries Against Polynomial-Based MACs and GCM
    Atul Luykx, Bart Preneel [Eurocrypt '18]

- Fast convolution sieving recovers $H(M) \oplus H(M')$ with $\tilde{\mathcal{O}}(2^{2n/3})$ queries and computations
  - First universal forgery attack with less than 2^n operations

Bonus algorithm

Citation [Luykx & Preneel, Eurocrypt'18]

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Optimal queries and memory complete sieving

Guess first half of difference.

  Run Known-prefix sieving over second half.

Repeat until found.

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Time is still $\tilde{\mathcal{O}}(2^n)$ but memory reduced to $\mathcal{O}(2^{n/2})$ in the nonce-respecting CPA model.

Conclusion

We defined the **missing difference problem** and **improved** the algorithms to solve it in particular for some cases:

Case	Previous	This work	Improved attacks
$\mathcal{S}$ affine subspace of dim $n/2$	$\tilde{\mathcal{O}}(2^{3n/4})$	$\tilde{\mathcal{O}}(2^{n/2})$	CTR plaintext recovery
No prior info *ie.* $\|\mathcal{S}\| = 2^n$	$\tilde{\mathcal{O}}(2^{n})$	$\tilde{\mathcal{O}}(2^{2n/3})$	GMAC, Poly1305 universal forgery

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Main take away :

- CTR mode not more secure than CBC (Sweet32).
- Frequent rekeying away from birthday bound will prevent these attacks.

Known-prefix Sieving Simulation

We challenge the heuristic assumptions we made (independence of the XORs $\{a \oplus b\}$). Approximations seem good enough.

Ran simulations with $n = 64$ bits and $z = n/2 = 32$ zeros.

- Each round we compare two lists of $2^{n/2}$ elements.
- Each round we expect $2^{n/2}$ partial collisions.
- Coupon collector predicts $n/2 \cdot \ln(2) \cdot 2^{n/2}$ partial collisions to recover S, that is 23 rounds on expectation.
- Simulation gives an idea of what is hidden in the $\mathcal{O}$ notations.

Consistent speed of leaking

In every runs, after 16 rounds the sieve was left between 419 and 560 candidates of S only.

Known-prefix Sieving Simulation

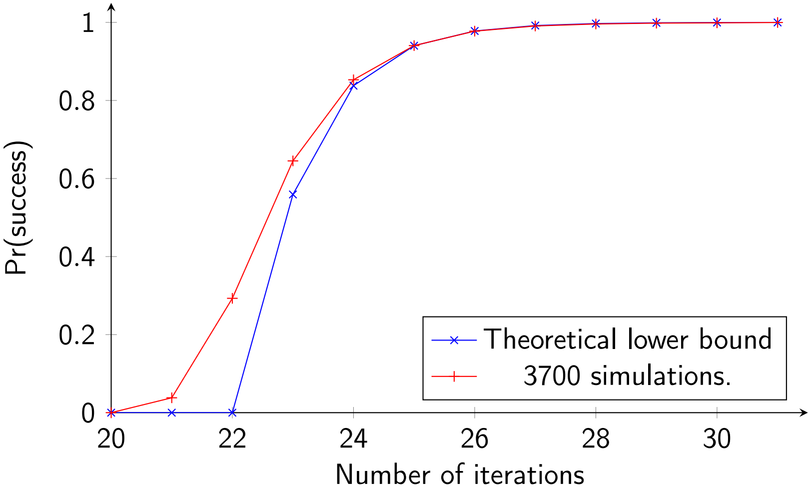
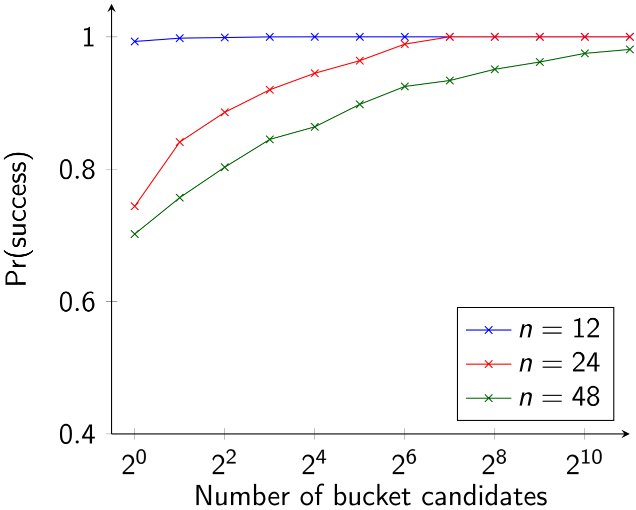


Figure: Probability of success of the known prefix sieving knowing 2^{32} encryptions of a 32-bit secret against the number of chunks of 2^{32} keystream blocks of size $n = 64$ bits used.

Fast Convolution Simulation

Figure: Results for $\sqrt{n}2^{2n/3}$ data; counting over $2n/3$ bits.



Works comparison

We independently described roughly the same attack on GCM, yet luckily our works complete each others:

Leurent & Sibleyras, EC'18

- Computational model
- Focus on **algorithms**
- Run simulations
- Provide a range of novel techniques and trade-offs
- Approach extendable to forgery on CWC mode

Luykx & Preneel, EC'18

- Information theoretic model
- Focus on **proofs**
- More rigorous analysis
- Show optimality w.r.t the best proofs
- Approach extendable to the KPA setting